

A MODELLER-SIMULATOR FOR INSTRUMENTAL PLAYING OF VIRTUAL MUSICAL INSTRUMENTS

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ABSTRACT

This paper presents a musician-oriented modelling and simulation environment for designing physically modelled virtual instruments and interacting with them via a high performance haptic device. In particular, our system allows restoring the physical coupling between the user and the manipulated virtual instrument, a key factor for expressive playing of traditional acoustical instruments that is absent in the vast majority of computer-based musical systems. We first analyse the various uses of haptic devices in Computer Music, and introduce the various technologies involved in our system. We then present the modeller and simulation environments, and examples of musical virtual instruments created with this new environment.

1. INTRODUCTION

An instrument can be described as a physical object used by humans to enhance their communication and interaction skills with the rest of the world. There is a physical coupling between the user and the instrument, a permanent energetic flow between the two parties, which intimately correlates the physical output of the instrument to the energy and nature of the human's input gestures. Cadoz defines this as the ergotic function of a gesture [1]. Acoustical musical instruments transform the user's gestures into sounds, energetically coupling mechanical gestures and aero-acoustical phenomena. This coupling is tightly linked to the expressiveness of these instruments.

Computer-based musical systems use digital algorithms to generate sound, and many interactive computer-based musical instruments do so according to user input gestures. Most of these systems completely separate the gestural input and sound production stages, breaking the action-sound chain found in acoustic instruments.

However, recent studies point out the relevance of the musician-instrument energetic coupling in a digital context [2,3,4]. In this paper we present technologies for restoring energetic coupling with simulated musical instruments, and a general framework for crafting and instrumentally playing virtual instruments, restoring the complete ergotic action-sound chain in a digital context.

2. HAPTICS IN DIGITAL MUSIC SYSTEMS

Haptic devices present exciting possibilities for restoring physical coupling between a user and a digital system. Many computer-based musical systems now employ haptic technologies, for a variety of purposes. We classify the associated recent literature into three categories of motivations and uses of haptic devices in Computer Music systems, described below:

2.1. A categorisation of haptic digital musical systems

Haptic devices are researched-on and used either:

1. To convey relevant information about a digital musical system to the musician's tactile-kinaesthetic perception, by displaying haptic cues (haptic display) [5,6].
2. To program the mechanical behaviour of a gestural controller, while maintaining mapping strategies for standard sound synthesis processes. Haptic models are used to adjust or extend the ergonomics of the gesture device [7,8].

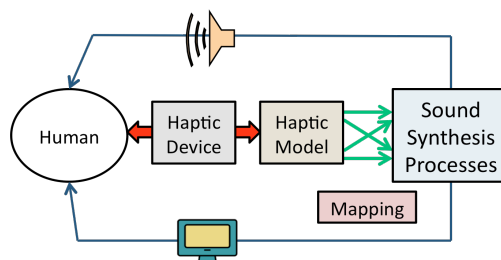


Figure 1: Addition of haptic feedback to mapping-based control of digital sound synthesis processes

3. To physically interact with a simulated instrument including its acoustical parts, aiming to restore the instrumentality found in acoustic instruments [2,3,4].

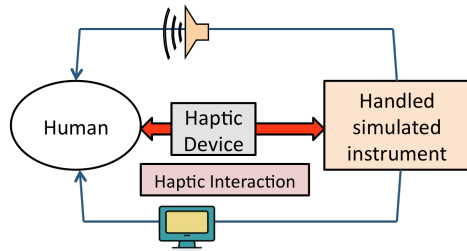


Figure 2: Direct, closed-loop haptic interaction with a simulated musical instrument

The systems in cases 1 and 2 are usually grounded on a classic mapping-based architecture between gestures and sounds, extending the gestural control section with haptic feedback (Fig 1). In most cases this can be relevantly achieved with classic haptic devices and asynchronous simulation architectures [5,7].

The third scenario (Fig 2) contains physical interaction between all the parts of the virtual instrument, from gestures to sounds, which implies much harder technological constraints. The present article focuses on this particular situation.

2.2. Physical interaction with simulated instruments

Historically, work targeting to restore instrumentality in the digital musician-sound relationship began in the 70's at ACROE-ICA, and has gained interest in recent years [2,3].

In this context, haptic devices are used as a direct interface between the human and a virtual simulated vibrating instrument, aiming to represent a complete instrumental situation between the two.

Recent experimental studies [4] have evaluated the role and importance of the ergotic action-sound relation in digital musical instruments, in particular for real time haptic playing of bowed string instruments. Both qualitative and quantitative evaluations of the system show that the action-sound chain bears importance, resulting in an improved "feel" of the instrument and also better success rates for non-trivial musical gestures such as reversing the direction of the bow while maintaining the vibration of the simulated bowed string.

This suggests that the physical coupling with the virtual instrument allows for enactive learning processes. Indeed haptic interfaces can constitute a platform for embodied cognition between the user and a virtual environment [9]. Therefore, we believe that creating digital musical instruments that restore the action-sound relation is of utmost importance for their resulting expressiveness. However, bringing together all the necessary technologies for these instruments is a complex task.

3. CONSTRAINTS FOR RESTORING THE ERGOTIC ACTION-SOUND CHAIN

The ERGON_X platforms developed at ACROE-ICA are specifically designed to fulfil all necessary conditions for obtaining a full ergotic action-sound chain. Below, we list the main requirements and corresponding features of these haptic simulation platforms.

3.1. High dynamic response and high peak force feedback from the haptic device

The device must correctly cover the dynamics of the real world instrumental coupling [10].

ACROE-ICA's research on technologies for real time multisensory interaction with simulated instruments has led to the design of a high performance haptic device, the TGR (*transducteur gestuel rétroactif*) [11,12], used in the ERGON_X platforms. It is composed of N one degree of freedom (DoF) keys, displays a 20 kHz mechanical bandwidth, and can generate peak forces up to 200 N. Multiple keys can be assembled with a variety of end effectors, such as 2 DOF bows, 3 DoF joysticks, pliers or 6 DoF stylus devices, or 1D piano keys (Fig 3).



Figure 3: A TGR with a 12 key Piano setup

The TGR haptic systems used in our ERGON_X platforms are the only devices to completely meet our demands concerning:

- The dynamic bandwidth of the device, which must be adequate regarding the rate of the simulations. Hands-on and precise interaction with simulated vibrating structures implies that the haptic device must be able to faithfully relay the audio-rate deformations of the object to the user. The importance of this feature has been evaluated in [4].
- The adaptability to a wide variety of musical gestures, through various interchangeable end-effector configurations.
- The ability to display contacts with similar rigidity to that of the mechanical/gestural sections of real world musical instruments, such as piano key mechanisms, fretting gestures, bowing, picking, etc. The high peak force feedback of the TGR allows simulating very hard contacts (knocking on a wooden table for instance), which are common in everyday interactions in the real world.

3.2. A single physically based model of the virtual object

Acoustic and mechanical sections of musical instruments, as well as the user's gestures, interact bilaterally with one another, acting on and receiving physical feedback. A single physically based mechano-acoustical model represents our virtual objects. Therefore, the interaction is a true audio-haptic physical interaction.

This is achieved by using the CORDIS ANIMA formalism [13]. It is a modular language for creating and simulating physical objects by building mass-interaction networks based on Newtonian physics. It defines a small number of physical modules that represent elementary physical behaviours, and can be assembled to build complex physical objects. Modules are split into two categories: <MAT> (mass-type) and <LIA> (interaction-type).

3.3. Hard real time synchronous simulation loop

The simulation must be based on a hard real time synchronous simulation loop [10], into which the signals relative to the haptic device are integrated. The simulation rate must also cover the temporal ranges of the entire active and perceptive sensory phenomena at the interface of the user and the virtual object.

In the ERGON_X platforms, real time physical simulations run on a TORO DSP Board from Innovative Integration, which interfaces the haptic device with the simulated object and calculates the physical simulation. The TORO presents two main advantages:

- The ability to interface up to 16 ADC and 16 DAC channels with the simulated model, with no latency.
- The ability to run completely reactive single-sample synchronous simulations at rates such as 44.1 kHz. The embedded computation is completely deterministic.

While simulating our physical models on a general purpose platform could allow for increased computing power, it would necessarily induce a trade-off concerning the reactivity of the simulation platform, hence the attainable simulation rate.

Therefore, the DSP board is a particularly appropriate solution for mono-frequency, 44.1 kHz audio-haptic simulations of virtual musical instruments.

The above technologies are at the heart of ACROE-ICA's research on real time multisensory interaction with simulated instruments and have enabled experiments such as [4]. A natural next step is to place these novel tools into the musician or composer's hands, for them to be used and further explored in practical musical creation situations. For this, a comprehensive full modelling/simulation environment is needed.

A few haptic modelling/simulation environments for sound exist in the literature [14,15], though so far none of them have targeted instrumental interaction. Our work showcases an environment for designing physically modelled virtual musical instruments and physically interacting with them in real time via the ERGON_X haptic platforms, restoring the energetic coupling between the musician and sound.

4. A MUSICIAN-ORIENTED PHYSICAL MODELLING ENVIRONMENT

4.1. The GENESIS modelling environment

GENESIS [16] is the main software environment developed by ACROE-ICA for musical creation with physical models. It possesses elaborate tools to create, edit, and tune physical structures, whose vibratory behaviour generates sound. GENESIS uses a specific implementation of CORDIS-ANIMA:

- Physical objects in GENESIS are designed in a 1D geometrical space, meaning that all mass-type modules move along a single vibration axis. 1D modelling is sufficient to generate nearly all perceptible aero-acoustic phenomena of vibrating structures [16] and reduces computing and modelling costs.
- GENESIS implements a subset of CORDIS-ANIMA modules, which are relevant for the creation of vibrating objects, such as masses, fixed points, springs, buffer-springs, viscosity and non-linear interactions.

All GENESIS models are simulated at a rate of 44.1 kHz, in order to respect the aero-acoustic phenomena generated by the simulated vibrating objects. GENESIS models were, until now, simulated exclusively offline: the simulation engine calculates the evolution of the model from its initial state.

Very large models can be designed, including precisely timed musical gesture metaphors, such as picking, striking, bowing, damping... GENESIS can also encompass compositional metaphors through physical structures, allowing for full musical compositions generated by a single physical model. Therefore, it is

not limited to a sound synthesis process; it serves the purpose of a full support for musical creation, based on physical models. Fig 4 shows a full musical piece composed in GENESIS, with tens of thousands of interacting components.

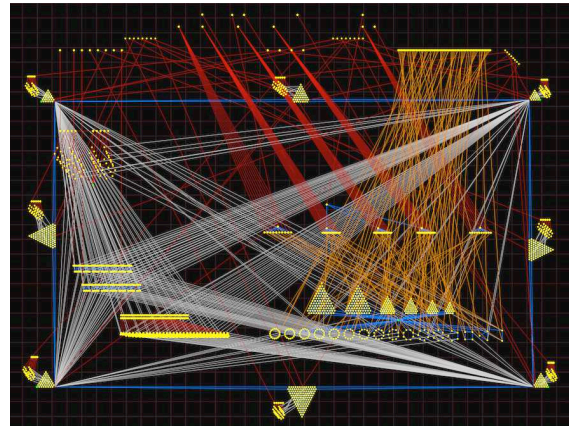


Figure 4: A complete musical composition created in GENESIS (pico..TERA, by C. Cadoz) composed of tens of thousands of interacting physical modules.

4.2. Modelling for real time haptic interaction

The GENESIS modelling environment is perfectly suited for modelling virtual objects for real time haptic interaction, thanks to its modularity and ease of use.

Furthermore, a large knowledge base of GENESIS physically modelled instruments has emerged over the years [17]. Although designing virtual instruments for real time haptic interaction does introduce a number of new modelling aspects, much of the experience acquired with GENESIS is transferable to real time simulations.

More specifically, new modelling aspects involve:

- Adjusting the physical equivalencies between the real world and simulated world.
- Introducing haptic device modules into the GENESIS modelling formalism.
- Taking the specificities of real time haptic simulation into account in the modelling process: optimising the model's behaviour in regard to the presence of a real world device in the simulation loop.

5. A NEW SIMULATION ENVIRONMENT

As stated in the previous section, GENESIS does not possess real time simulation capabilities and calculates models off-line. On the other hand, the ERGON_X platforms use dedicated hardware and software optimised for real time computation; however, they do not possess a dedicated modeller, since all physical models are directly coded in C++ for the DSP.

We have created a new prototype software environment for the real time haptic simulation of GENESIS models on ERGON_X platforms. These two technologies had never merged so far, due to several technological hard constraints. Our new simulation environment addresses these issues, resulting in a musician-oriented prototype modeller/simulator for instrumental interaction with simulated musical instruments.

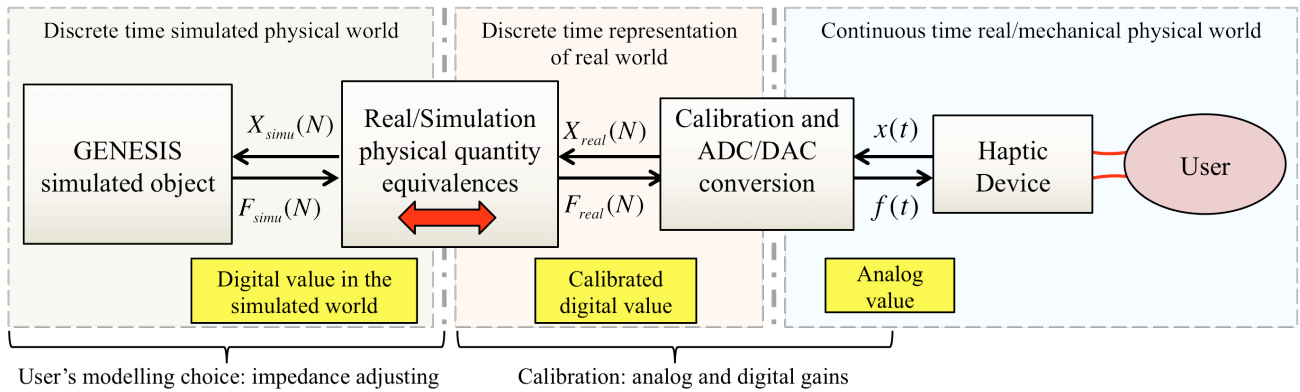


Figure 5: From the user to the simulated object: the full real/simulation loop.

5.1. A new simulation engine

The first crucial aspect for enabling real time simulation of GENESIS instruments is the simulation engine itself. The GENESIS engine is conceived to be entirely modular, meaning that any physical network designed in the modelling environment can be automatically allocated in the simulation engine, and then simulated offline. On the other hand, the ERGON_X simulation engine is designed for maximum simulation speed on the TORO DSP chip (C6711 from Texas Instruments). The simulation algorithms are hand-written and optimised for each specific model, thus breaking the engine's modularity.

Simulation constraints for a real time modeller/ simulator encompass both of the above aspects: modular design and synchronous real time simulation on DSP.

Tests on the GENESIS and ERGON_X engines confirmed that they were not, as such, fit for our needs. Consequently, several new simulator architectures were created and tested using a specially created bench-testing framework, with various data structures, simulation allocation techniques, and expressions of the CORDIS-ANIMA algorithms.

The result of this work is a new modular, synchronous, hard real time CORDIS-ANIMA simulation engine that runs fully at 44.1 kHz, specifically optimised for the TORO DSP chip. It uses a new data structure, with static memory allocation, and fully reorganises the physical model for vectorised algorithmic computation, using DSP-optimised expressions of the CORDIS-ANIMA algorithms. This simulator retains similar performance to the ERGON_X engine, while allowing for full modularity (inhomogeneous topologies and parameters), as shown in Table 1.

Table 1. Performance of the new simulation engine compared to the previous GENESIS and ERGON_X engines.

	Maximum Complexity (nb. of modules vs. simulation sampling rate)
ERGON_X engine	Approx. 200 modules at 44.1 kHz, optimised with homogenous topology and parameters
GENESIS engine	Approx. 20 modules at 44.1 kHz.
New Simulation Engine	Approx. 140 modules at 44.1 kHz, fully inhomogeneous topology and parameters

5.2. Real/Simulation Interconnection

Surprisingly, little literature on haptic simulation systems focuses on system calibration and quantitative, measurable real/simulation equivalencies. Representing GENESIS instruments in the real world via a haptic interface introduces a number of new questions and challenges, which we have addressed with work described in the following section.

5.2.1. Impedance scales in GENESIS models

GENESIS gives users the freedom of creating physical objects at various physical scales. A minuscule, microscopic object and the same object blown up to a colossal scale can produce completely identical normalised audio output. A major appeal of this freedom of scales lies in the possibility of making various physical scales cohabitate within a single physical model, and in adjusting the retroaction properties between different subsections of the model. This can result in complex and rich emerging physical behaviours.

We have deemed essential to allow the user to interact with objects at any scale inside the model, while retaining the energetic consistency of the interaction. This requires representation factors between the real world and the simulation, not only for spatial dimensions but also for impedance.

5.2.2. Quantitative understanding of the real/ simulation interconnection and mediation to the user

Three parameters define the static mode interconnection properties between the real world and the simulation:

- The real/simulation position gain.
- The simulation/real force feedback gain.
- The sampling rate of the simulated world.

These parameters play a double role:

- They allow calibration of the system, ensuring best precision and full control of the position and force feedback signals throughout the whole simulation chain, including compensation of the electronics and conditioning of the position and force signals for optimal precision from the ADC and DAC converters.
- They determine the relations between measurable physical quantities in the real world and physical quantities defined in the simulated model, expressed with model-space parameters, thus defining the model's behaviour in the real world.

Fig 5 shows the separation between these two roles. The calibration of the system is an advanced procedure for expert users who are familiar with the haptic device. On the other hand, real/simulation impedance adjusting is a modelling choice, to be defined and freely adjusted by the user depending on his simulated instrument. Therefore, it must be presented in an intuitive yet complete manner in the user interface.

The original ergonomics proposed in our prototype software environment separate calibration gains from the physical equivalency adjustment. The modelling choice of the real/simulation equivalencies is presented to the user through a table of static mode physical value equivalencies, displaying all equivalencies between real world quantities and model-space quantities. The user can configure the real/simulation interconnection by setting a specific equivalency for a given physical quantity, which then computes the adequate position and force feedback gains and updates all other real/simulation relations.

As stated previously, several impedance scales may cohabitate inside a single GENESIS model. For this purpose we propose one global real/simulation equivalency as a basis for the whole system, and allow additional per-key fine-tuning with different interaction properties for interactions with different sections of the instrument.

This procedure allows complete quantitative control of the interaction properties with GENESIS instruments.

6. CREATING REAL TIME GENESIS INSTRUMENTS

Our new modeller/simulator gathers all the necessary conditions for playing GENESIS models with energetic coherency. We will now describe the typical procedure for the creation of real time GENESIS instruments and show two examples of virtual instruments built with this new system.

6.1. Typical workflow for the design of real time GENESIS instruments

Step 1: Instrument design

The first step to design the virtual instrument is creating it in the GENESIS modelling environment. The physical model can be adjusted, tuned and simulated off-line without haptic interaction in order to calibrate the acoustical and mechanical properties of the object. Several logical representations of the haptic device can then be integrated into the model and connected to the vibrating or mechanical sections via interactions such as plucking, bowing, striking or pinching/fretting mechanisms, all of which are entirely designed by assembling standard CORDIS-ANIMA modules. The representations of the haptic device are <MAT> (mass-type) modules, receiving a force input from the model's calculated force feedback and providing a position output measured by the TGR haptic device's sensors.

Step 2: Hardware mapping and configuration

Once the model of the virtual instrument has been created in GENESIS, it can be imported into the new real time software environment. At this stage, the user maps the model's logical representations of the haptic device to the actual hardware configuration of the TGR and adjusts the interaction properties between the user and the simulated object, via the real/simulation interconnection configuration. The model description is now complete, including the full haptic interaction connections and properties.

Step 3: Compiling and running the simulation

The last step consists in compiling the model description and the TGR properties into an optimised real time DSP binary application, which is then loaded on to the TORO DSP board. The user is now ready to launch the simulation, and experiment multisensory instrumental playing of the model, with haptic, audio and visual feedback.

The simplicity of this whole process allows for an efficient modelling/simulation loop, making the prototyping and experimental testing of new instrument designs very easy for the end-user, even if he or she has little to no prior knowledge about the underlying technology.

6.2. Some examples

Our first model is inspired by the classic piano mechanism. It makes full use of the ERGON_X platform, with twelve individual keys (Fig 6). Each one is connected to a small hammer, which strikes a vibrating structure when the Piano key is moved. Each key is also connected to a fixed point via a buffer-spring interaction, which models the hard contact when the key is fully pressed down. The vibrating structures are simple dampened oscillators connected to a bridge that captures all the vibrations. This reduces the complexity of the model since the DSP computing power is limited when simulating at 44.1 kHz.

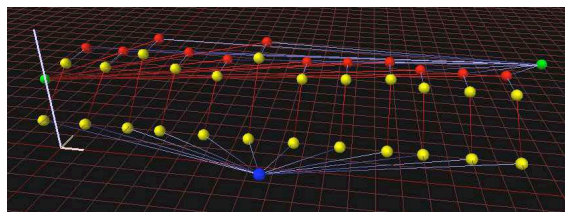


Figure 6: *The Piano Model during real time simulation.*

The modelling process encompasses the full design of the instrument: the mechanical feel, as well as the sounding structures. Depending on the complexity of the model, it is possible to adjust the feel of the instrument in a similar way to Gillespie's haptic keyboard [9]. In the above model, the mechanical feel is certainly somewhat simplified, however the real novelty is the full physical connection: the mechanical design and behaviour is intimately tied to the sound and playability, and the instrument is crafted as a whole in consequence.

The second example is composed of one vibrating structure: a string fixed at both ends. Several interaction mechanisms are designed around this string: the user can pluck it, via a non-linear interaction, dampen the string at specific harmonic nodes in order to obtain natural harmonics (Fig 7), and also pin the string down as one would with a fretting hand, changing the pitch.

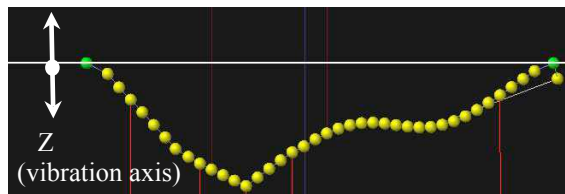


Figure 7: *Zoomed-in screenshot of a string model during real time simulation. The string is plucked then dampened at a third of the length, resulting in a natural harmonic a 5th above the open string pitch.*

These various actions all influence the resulting sound in a natural yet subtle manner, including non-linear occurrences during the pinching and plucking of the string. These intrinsic physical phenomena are intimately linked to the energetic coherency of the whole system.

These models are presented as some of the first creations and explorations with our new platform. The main novelty we introduce is the ability to create virtual instruments simply and intuitively with GENESIS, to play them in real time and in an instrumental fashion, go back to the modelling stage and adjust the behaviour of the instrument, experiment with it again... The process of creating and fine-tuning various new ideas and designs of haptic virtual musical instruments is very efficient, and is finally accessible to users without a technical background. Modelling various haptic virtual musical instruments with this platform and creating new interaction schemes with them is an on-going activity, which we are excited to continue studying and perfecting in the near future.

7. CONCLUSIONS

In this paper we have presented a first prototype modeler/simulator for musical creation with instrumental interaction. For the first time, GENESIS instruments can be touched, played and experimented with, opening the way for improvisation, exploration and new means of interactive musical creation with simulated instruments. By maintaining the energetic link between the user and the instrument we can achieve rich musical interaction, ultimately aiming to recreate an enactive natural instrumental situation.

This work opens the domain of virtual instrument design and real time playing to musicians and composers, avoiding the need for technical computing knowledge but still giving the user entire comprehensive control of both the modelling and the simulation processes. The user can change and perfect his/her instrument's playability and sound, change the way of interacting with it, and create instruments that do not or could not exist in the real physical world. As a whole, the ergotic quality of our interactions with simulated instruments opens a vast number of new creative possibilities with GENESIS.

Our system is also a promising base for further quantitative exploration of the role of the ergotic function in the context of manipulating simulated musical instruments. Indeed, it is now very easy to implement a vast number of different virtual instruments with different types of physical interactions between musician and instrument, which will allow for new experiments and evaluations.

This first work is a prototype upon which we aim to build. We are currently studying the extension of our modelling and simulation platform to accommodate multirate physical models simulated on a distributed DSP/ real time host architecture, allowing for much more computing power, resulting in larger and musically richer models. We also aim to integrate the various TGR end-effectors into our system and increase the complexity of the gesture interaction, by enabling 24 key models connecting several ERGON_X platforms. Finally, our real time haptic simulation features will be integrated into mainline GENESIS.

8. ACKNOWLEDGMENTS

This research has been performed with the support of the French Ministry of Culture and of the French Agence Nationale de la Recherche through the cooperative project DYNAMÉ - ANR-2009-CORD-007. Many thanks to A. Luciani for her contribution to this work.

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